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¹⁴C wiggle-matching of short tree-ring sequences from post-medieval buildings in England

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Abstract

This study tests whether accurate dating by AMS radiocarbon wiggle-matching short tree-ring series (c. 30 annual rings) in the period after AD 1510 can be achieved routinely. Such an approach has proved problematic for some intervals in the period AD 1160–1541 (Bayliss *et al.* 2017), which are before single-year calibration data are available (Stuiver 1993). We suggest that such calibration data are essential if this approach is to be employed for the informed conservation of standing buildings.

Keywords

¹⁴C; AMS; radiocarbon wiggle match; radiocarbon calibration

1. Introduction

Over the past 25 years scientific dating has become an integral part of the processes for conservation and repair of historic buildings in England. Precise dating informs decisions about the preservation of buildings, allows us to identify significant fabric, and aids in the specification of appropriate repair

1 strategies. Small differences in date can lead to great differences in the
2 significance of the extant building, and thus to great differences in the costs of
3 the agreed solution for a particular structure.
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7 In providing the required precise dating for historic buildings, the scientific
8 dating method of choice is dendrochronology. In some cases, however, tree-
9 ring analysis does not provide calendar dating, usually either because there
10 are insufficient growth rings in the timbers or because they are of a species
11 that is unsuitable for dendrochronology. In these cases, radiocarbon wiggle-
12 matching is needed to provide an equivalent level of precision and reliability.
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20 **2. Material and Methods**

21 Radiocarbon wiggle-matching has previously been undertaken on part of a
22 303-ring pine series dated by dendrochronology to AD 1367–1670 from
23 Jermyn Street, London (Tyers *et al.* 2009). In this study, measurements from
24 three participating AMS laboratories all provided accurate wiggle-matches
25 from ring series covering a century or more. Insufficient data are available
26 from this core, however, to undertake wiggle-matching on shorter sequences.
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34 For this reason, new measurements were obtained on a 149-ring core, LED-
35 A22, from the east principal rafter in truss 3 of one of the roofs of Ledston
36 Hall, West Yorkshire (1.34104 W, 53.75494 N). The growth-rings in this timber
37 span AD 1520–1668, with 20 rings of sapwood and bark edge surviving. It is
38 part of a site sequence, LEDASQ01, which is dated by dendrochronology to
39 AD 1424–1668 (Table 1). The ring-width data of the series are provided in
40 Arnold *et al.* (2015).
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50 Radiocarbon measurements were made on a total of 60 single-year tree-ring
51 samples from this core in 2016–17. The 17 dated at the Scottish Universities
52 Environmental Research Centre were prepared to α -cellulose, combusted,
53 graphitised, and dated by AMS as described by Dunbar *et al.* (2016). The 18
54 dated at the Oxford Radiocarbon Accelerator Unit were processed using an
55 acid-alkali-acid pretreatment followed by bleaching with sodium chlorite as
56 described by Brock *et al.* (2010, table 1 (UW)), graphitised (Dee and Bronk
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1 Ramsey 2000), and measured by AMS (Bronk Ramsey *et al.* 2004). The 14
2 dated at the Bristol Radiocarbon Accelerator Mass Spectrometry Facility were
3 processed using the base-acid-base-acid-bleach method as described by
4 Némec *et al.* (2010), graphitised using an IonPlus AGE3 graphitisation system
5 (Wacker *et al.* 2010), and measured using a MICADAS AMS (Synal *et al.*
6 2007). The 15 dated at the TUBITAK were pretreated using the acid-alkali-
7 acid method modified from Hadjas *et al.* (2004), graphitised (Wacker *et al.*
8 2010) and measured by AMS on a 1 MV NEC Pelletron accelerator.
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16 At Oxford and SUERC, $\delta^{13}\text{C}$ values, relative to VPDB, were obtained by IRMS
17 from the gas combusted for graphitisation; at BRAMS and TUBITAK $\delta^{13}\text{C}$
18 values were measured by AMS.
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24 The conventional radiocarbon ages reported for these samples, along with the
25 rings dated, are listed in Table 2. The quoted errors are each laboratory's
26 estimates of the total error in their dating systems. Five pairs of replicate
27 radiocarbon measurements are available on rings dated to the same calendar
28 year, all of which are statistically consistent at 95% confidence (Ward and
29 Wilson 1978; Table 2). This scatter is in line with statistical expectation. Only
30 two of the replicate $\delta^{13}\text{C}$ values are statistically consistent at 95% confidence,
31 one is inconsistent at 95% confidence, but consistent at 99% confidence, and
32 two are significantly different at more than 99% confidence (Ward and Wilson
33 1978; Table 2). These results are more scattered than would be expected on
34 statistical grounds. This suggests that the different pre-treatment protocols
35 used for wood samples by the Oxford and SUERC laboratories may be
36 affecting the $\delta^{13}\text{C}$ values, especially since replicate $\delta^{13}\text{C}$ values on bone
37 samples reported by the two laboratories in the same period are in much
38 better agreement (Bayliss *et al.* 2016, fig. 14).
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53 Forty-two pairs of replicate measurements, 17 groups of triplicate
54 measurements, and one quadruple group of measurements are also available
55 on rings dated by AMS (this study) and gas proportional counting Stuiver
56 (1993) to the same calendar year (Figure 1). Of these 60 sets of radiocarbon
57 ages, 52 groups are consistent at 95% confidence, 6 groups are consistent at
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99% confidence, and two inconsistent at more than 99%. This scatter is rather more than would be expected simply on the basis of statistics. Stuiver (1993) reported counting errors only, however, and, when the errors quoted for this dataset are inflated using the laboratory error multiplier suggested by Stuiver *et al.* (1998, 1045), 56 sets of measurements are consistent at 95% confidence and the remaining four at 99% confidence, which is within statistical expectation.

3. Wiggle-matching the entire sequence

Wiggle-matching has been undertaken using the Bayesian approach first described by Christen and Litton (1995), implemented using OxCal v4.2 (Bronk Ramsey 2009) and the IntCal13 atmospheric calibration data for the northern hemisphere (Reimer *et al.* 2013).

Figure 2 shows the model for the entire sequence of data from Ledston Hall. This has good overall agreement (Acomb: 70.2, An:9.1, n:60; Bronk Ramsey *et al.* 2001), and estimates the final ring of the sequence to have been formed in *cal AD 1664–1671 (95% probability; SUERC-68040; Fig 2)*. This is compatible with the date of AD 1668 produced for this ring by dendrochronology (Table 1).

Wiggle-matching was then undertaken separately of the radiocarbon results quoted by each laboratory (Figs. 3a–b and 4a–b). The model composed of measurements made in Bristol has good overall agreement (Acomb: 102.8, An: 18.9, n: 14; Fig. 3a) and estimates that the last ring of the timber formed in *cal AD 1658–1672 (95% probability; Ring 149)*, probably in *cal AD 1662–1670 (68% probability)*. The model of measurements made at Oxford also has good overall agreement (Acomb: 30.9, An: 16.7, n: 18; Fig. 3b) and estimates the last ring of the timber to have formed in *cal AD 1655–1670 (95% probability; Ring 149)*, probably in *cal AD 1657–1664 (68% probability)*.

Results from SUERC also have good overall agreement (Acomb: 109.9, An: 17.1, n: 17; Fig. 4a) and suggest that the last ring of the timber formed in *cal AD 1656–1674 (95% probability; SUERC-68040)*, probably in *cal AD 1662–1671 (68% probability)*. The wiggle match for TUBITAK measurements also

1 have good overall agreement (Acomb: 75.0, An: 18.3, n: 15; Fig. 4b) and
2 suggest that the last ring of the timber formed in *cal AD 1661–1679 (95%*
3 *probability; ring_149)*, probably in *cal AD 1665–1674 (68% probability)*. In all
4 cases the estimated date of the final ring (*at 95% probability*) includes the
5 felling date provided by dendrochronology of AD 1668.
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10 **4. Wiggle-matching partial sequences**

11 Given that the length of the available tree-ring sequence is the most common
12 limitation on successful dendrochronology in historic buildings from England,
13 we ran a series of 25 short wiggle-matches on blocks consisting of between
14 29 and 30 rings. The results on the seven dated rings in each block were
15 incorporated into a wiggle-match model that estimated the date of the final
16 ring of the complete core. These estimates could then be compared with the
17 known date for the final ring as derived from dendrochronology (AD 1668) to
18 determine the accuracy of the short wiggle-matches.
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29 The results are given in Table 3 and summarised in Figure 5. The Highest
30 Posterior Density interval at 95% probability includes the tree-ring date for the
31 final ring of LED-A22 (AD 1668) in all cases, and the interval at 68%
32 probability includes the tree-ring date in all but four cases. This
33 correspondence between the results of the wiggle-matching and the
34 dendrochronology is greater than statistical expectation.
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42 **5. The long wiggle-match (AD 1160–1668)**

43 As illustrated in Figure 2, a wiggle-match comprising the radiocarbon
44 measurements on the 45 dated rings from Ledston Hall has good overall
45 agreement (Acomb: 70.2; An: 9.1; n: 60) and produces posterior distributions
46 that are compatible with the dendrochronology (AD 1668). Similarly, the
47 wiggle-match including the results on the 18 dated rings from Jermyn Street
48 (Tyers *et al.* 2009, fig. 4) has good overall agreement when recalculated using
49 IntCal13 (Acomb: 35.3; An: 16.7; n: 18) and also produces posterior
50 distributions that are compatible with the dendrochronology (AD 1670).
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1 In contrast, the wiggle-match including the radiocarbon measurements on the
2 79 dated rings from the sites considered by Bayliss *et al.* (2017, fig 9) has
3 poor overall agreement (Acomb: 1.6; An: 8.0; n: 79), and the Highest
4 Posterior Density interval for the final ring does not include the date obtained
5 for this ring by dendrochronology (AD 1544) even at 99% probability.
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10 When the entire dataset is combined to form a wiggle-match sequence
11 covering AD 1160–1668, the model has poor overall agreement (Acomb: 1.7;
12 An: 6.4; n: 121), and the Highest Posterior Density interval for the final ring
13 does not include the date obtained for this ring by dendrochronology (AD
14 1668) even at 99% probability.
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22 **6. Discussion**

23 These studies in combination suggest that wiggle-matching of either short (c.
24 30-ring) or long (more 100-ring) tree-ring sequences produces results that are
25 compatible with dendrochronology in the period after AD 1510. In the
26 centuries before this, there appears to be time periods when wiggle-matching
27 does not produce such accuracy (AD 1240–1306 and AD 1396–1532; Bayliss
28 *et al.* 2017, table 6).
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36 This pattern is observed when considering the datasets measured at Oxford
37 and SUERC separately (Bayliss *et al.* 2017, table 5; Tyers *et al.* 2009, table 3;
38 Figs. 3b and 4a), and so must derive from the calibration curve used, IntCal13
39 (Reimer *et al.* 2013).
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45 Figures 6–7 shows the radiocarbon ages obtained on single known-age tree-
46 rings as part of this study and those reported by Tyers *et al.* (2009) and
47 Bayliss *et al.* (2017) in comparison to the radiocarbon ages covering this
48 period included in IntCal13 (Reimer *et al.* 2013). The latter are on decadal
49 samples (Wk; Hogg *et al.* 2002), single-year and decadal samples (QL;
50 Stuiver 1993, corrected as described by Stuiver and Becker 1993; Stuiver *et al.*
51 1998), decadal and bi-decadal samples (UB; Hogg *et al.* 2002; Pearson *et al.*
52 1986), and decadal and 23-year and 24-year samples (GrN; van der Plicht
53 *et al.* 1995).
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1 Single-year data clearly dominate the period after AD 1510 (Fig 7), which is
2 the period when wiggle-matching appears to be accurate within the precision
3 quoted and the test data scatter within statistical expectation around the
4 IntCal envelope. In the earlier period, there is more deviation between the test
5 data and the IntCal envelope. As the statistical method of curve construction
6 is the same in both periods (Niu *et al.* 2013), this is unlikely to be the cause of
7 this difference, but rather there appears to be detailed structure in the
8 atmospheric concentration of radiocarbon in the problematic periods which is
9 not apparent from the calibration data currently available.

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11 It should be noted that, if accurate wiggle-matching is possible in the post AD
12 1510 period because of the availability of single-year calibration data, then it
13 is possible to accurately match measurements on samples of European wood
14 against calibration data measured largely on Douglas fir trees that grew on
15 the west coast of America. This would suggest neither intra-hemispheric
16 locational offsets in the ^{14}C concentration of wood (McCormac *et al.* 1995) nor
17 the translocation of ^{14}C between annual growth rings in trees (Grootes *et al.*
18 1989) are significant factors preventing accurate wiggle-matching.

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20 A calibration curve based on ^{14}C measurements on single tree-rings appears
21 to be required for wiggle-matching to provide estimates of calendar date that
22 are accurate to within the quoted uncertainty. Such accuracy is essential if the
23 results are to inform the long-term preservation and conservation of historic
24 buildings.

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Table 1: Results of cross-matching site chronology LEDASQ01 with relevant independent site reference chronologies

Reference chronology	t-value	Span of chronology	Reference
Riding House, Bolsover Castle, Derbyshire	12.0	AD 1494–1744	Arnold <i>et al.</i> 2005a
Pontefract Castle, Pontefract, West Yorkshire	11.0	AD 1507–1656	Arnold <i>et al.</i> 2005b
Little Castle, Bolsover Castle, Derbyshire	10.4	AD 1532–1749	Arnold <i>et al.</i> 2003
Clumpcliff Farm, Rothwell, West Yorkshire	10.2	AD 1452–1613	Howard <i>et al.</i> 2000
Auckland Castle, Bishop Auckland, County Durham	10.1	AD 1425–1698	Arnold and Howard 2013
Nun Appleton, Tadcaster, West Yorkshire	9.6	AD 1478–1657	Arnold <i>et al.</i> 2008

Table 2: Details of sampled tree-rings and radiocarbon results from LED-A22

Laboratory code	Material	¹⁴ C age (BP)	δ ¹³ C _{IRMS} (‰)	Tree-ring date (AD)
SUERC-68046	<i>Quercus</i> sp. heartwood, ring 1	306±29	-23.5±0.2	1520
TUBITAK-127	<i>Quercus</i> sp. heartwood, ring 3	321±29	-24.1±1.0	1522
OxA-34316	<i>Quercus</i> sp. heartwood, ring 4	311±33	-23.4±0.2	1523
OxA-34317	<i>Quercus</i> sp. heartwood, ring 4	357±35	-23.8±0.2	
Ring 4	333±25BP, T'=0.9; -23.6±0.14 ‰, T'=2.0; T'(5%)=3.8, v=1			
BRAMS-1230	<i>Quercus</i> sp. heartwood, ring 7	315±26	-21.9±0.2	1526
SUERC-68056	<i>Quercus</i> sp. heartwood, ring 9	324±29	-24.0±0.2	1528
OxA-34321	<i>Quercus</i> sp. heartwood, ring 9	359±33	-24.9±0.2	
Ring 9	339±22BP; T'=0.6; -24.5±0.14 ‰, T'=10.1; T'(5%)=3.8, v=1			
TUBITAK-128	<i>Quercus</i> sp. heartwood, ring 13	276±27	-23.5±1.0	1532
OxA-34275	<i>Quercus</i> sp. heartwood, ring 14	262±25	-24.9±0.2	1533
BRAMS-1231	<i>Quercus</i> sp. heartwood, ring 15	319±26	-22.9±0.2	1534
SUERC-68044	<i>Quercus</i> sp. heartwood, ring 19	282±29	-24.1±0.2	1538
TUBITAK-129	<i>Quercus</i> sp. heartwood, ring 21	352±50	-24.5±1.7	1540
BRAMS-1232	<i>Quercus</i> sp. heartwood, ring 22	294±26	-25.0± 0.2	1541
SUERC-68054	<i>Quercus</i> sp. heartwood, ring 24	315±29	-24.2±0.2	1543
OxA-34323	<i>Quercus</i> sp. heartwood, ring 24	380±33	-24.9±0.2	
Ring 24	344±22BP; T'=2.2; -24.6±0.14 ‰, T'=6.1; T'(5%)=3.8, v=1			
SUERC 68053	<i>Quercus</i> sp. heartwood, ring 29	322±29	-25.2±0.2	1548
OxA-34281	<i>Quercus</i> sp. heartwood, ring 29	255±25	-26.2±0.2	
Ring 29	284±19BP; T'=3.1; -25.7±0.14 ‰, T'=12.5; T'(5%)=3.8, v=1			
BRAMS-1233	<i>Quercus</i> sp. heartwood, ring 31	302±26	-26.1±0.2	1550

OxA-34277	<i>Quercus</i> sp. heartwood, ring 34	328±24	-24.3± 0.2	1553
TUBITAK-130	<i>Quercus</i> sp. heartwood, ring 36	307±27	-25.5±0.8	1555
SUERC-68051	<i>Quercus</i> sp. heartwood, ring 39	335±29	-24.6±0.2	1558
OxA-34319	<i>Quercus</i> sp. heartwood, ring 44	334±32	-25.4±0.2	1563
TUBITAK-131	<i>Quercus</i> sp. heartwood, ring 45	310±27	-25.3±0.8	1564
BRAMS-1234	<i>Quercus</i> sp. heartwood, ring 47	353±26	-22.4±0.2	1566
SUERC-68034	<i>Quercus</i> sp. heartwood, ring 49	306±29	-25.1±0.2	1568
OxA-34457	<i>Quercus</i> sp. heartwood, ring 54	364±27	-25.9±0.2	1573
BRAMS-1235	<i>Quercus</i> sp. heartwood, ring 56	382±26	-28.4±0.2	1575
TUBITAK-132	<i>Quercus</i> sp. heartwood, ring 58	290±48	-25.1±1.5	1577
SUERC-68035	<i>Quercus</i> sp. heartwood, ring 59	346±29	-25.8±0.2	1578
TUBITAK-133	<i>Quercus</i> sp. heartwood, ring 62	286±27	-26.7±0.8	1581
OxA-34279	<i>Quercus</i> sp. heartwood, ring 64	331±26	-25.9±0.2	1583
BRAMS-1236	<i>Quercus</i> sp. heartwood, ring 67	336±26	-25.8±0.2	1586
SUERC-68052	<i>Quercus</i> sp. heartwood, ring 69	310±29	-25.9±0.2	1588
OxA-34282	<i>Quercus</i> sp. heartwood, ring 74	297±26	-27.1±0.2	1593
TUBITAK-134	<i>Quercus</i> sp. heartwood, ring 77	396±29	-26.3±0.9	1596
SUERC-68036	<i>Quercus</i> sp. heartwood, ring 79	334±29	-25.6±0.2	1598
OxA-34283	<i>Quercus</i> sp. heartwood, ring 84	336±26	-26.4±0.2	1603
TUBITAK-135	<i>Quercus</i> sp. heartwood, ring 85	336±28	-24.9±0.9	1604
BRAMS-1238	<i>Quercus</i> sp. heartwood, ring 86	365±26	-24.4± 0.2	1605
SUERC-68050	<i>Quercus</i> sp. heartwood, ring 89	347±29	-25.2± 0.2	1608
OxA-34278	<i>Quercus</i> sp. heartwood, ring 94	341±25	-24.8±0.2	1613
TUBITAK-136	<i>Quercus</i> sp. heartwood, ring 96	416±42	-26.3±0.9	1615
BRAMS-1239	<i>Quercus</i> sp. heartwood, ring 98	370±26	-23.1±0.2	1617
SUERC-68042	<i>Quercus</i> sp. heartwood, ring 99	364±29	-23.7±0.2	1618
OxA-34318	<i>Quercus</i> sp. heartwood, ring 104	374±31	-24.1± 0.2	1623
TUBITAK-137	<i>Quercus</i> sp. heartwood, ring 107	351±27	-23.0±0.7	1626
SUERC-68055	<i>Quercus</i> sp. heartwood, ring 109	313±29	-23.8±0.2	1628
OxA-34322	<i>Quercus</i> sp. heartwood, ring 109	351±34	-24.1±0.2	
Ring 109	284±19BP; T'=3.1; -24.0±0.14 ‰, T'=1.1; T'(5%)=3.8, v=1			
BRAMS-1240	<i>Quercus</i> sp. heartwood, ring 110	348±26	-23.3±0.2	1629
OxA-34280	<i>Quercus</i> sp. heartwood, ring 114	321±26	-25.0±0.2	1633
TUBITAK-138	<i>Quercus</i> sp. heartwood, ring 115	312±26	-22.7±0.7	1634
SUERC-68043	<i>Quercus</i> sp. heartwood, ring 119	320±29	-22.9±0.2	1638
BRAMS-1241	<i>Quercus</i> sp. heartwood, ring 120	291±26	-22.7±0.2	1639
TUBITAK-139	<i>Quercus</i> sp. heartwood, ring 122	271±28	-24.0±0.9	1641
OxA-34284	<i>Quercus</i> sp. heartwood, ring 124	275±25	-25.7±0.2	1643
BRAMS-1242	<i>Quercus</i> sp. heartwood, ring 125	263±26	-25.7±0.2	1644
SUERC-68041	<i>Quercus</i> sp. heartwood, ring 129	214±29	-23.7±0.2	1648

BRAMS-1243	<i>Quercus</i> sp. heartwood, ring 131	301±26	-21.7±0.2	1650
OxA-34320	<i>Quercus</i> sp. heartwood, ring 134	292±32	-24.3±0.2	1653
TUBITAK-140	<i>Quercus</i> sp. heartwood, ring 135	212±29	-23.8±1.1	1654
SUERC-68045	<i>Quercus</i> sp. heartwood, ring 139	267±29	-23.4±0.2	1658
OxA-34276	<i>Quercus</i> sp. heartwood, ring 144	214±24	-24.2±0.2	1663
TUBITAK-141	<i>Quercus</i> sp. heartwood, ring 146	248±55	-26.3±2.3	1665
BRAMS-1244	<i>Quercus</i> sp. heartwood, ring 148	214±26	-21.9±0.2	1667
SUERC-68040	<i>Quercus</i> sp. heartwood, ring 149	222±29	-24.0±0.2	1668

Table 3: Summary of the estimated dates for the final ring of LED-A22 (dated by dendrochronology to AD 1668) from wiggle-matching 29–30-year blocks (An: 26.7, n: 7 for all).

Rings	Acomb	<i>Highest Posterior Density interval (cal AD)</i>	
		<i>68% probability</i>	<i>95% probability</i>
1–29	48.0	1660–1676 (59%) or 1683–1688 (9%)	1655–1709 (89%) or 1760–1770 (6%)
4–34	51.5	1659–1675	1655–1693 (93%) or 1700–1706 (2%)
9–39	50.8	1660–1675 (60%) or 1683–1687 (8%)	1655–1706
14–44	63.2	1664–1676	1657–1694
19–49	83.3	1655–1689	1645–1699
24–54	72.3	1650–1657 (10%) or 1665–1694 (58%)	1643–1706
29–59	90.6	1653–1678 (58%) or 1686–1692 (10%)	1647–1700
34–64	102.7	1655–1704	1596–1620 (11%) or 1634–1723 (84%)
39–69	95.1	1599–1615 (20%) or 1651–1682 (38%) or 1697–1704 (8%) or 1719–1721 (2%)	1593–1636 (27%) or 1642–1725 (68%)
44–74	95.7	1598–1617 (42%) or 1662–1670 (9%) or 1709–1722 (17%)	1595–1631 (44%) or 1640–1677 (26%) or 1695–1724 (25%)
49–79	91.5	1599–1617 (39%) or 1649–1670 (29%)	1592–1675 (80%) or 1694–1715 (15%)
54–84	98.4	1597–1618 (43%) or 1651–1668 (16%) or 1698–1707 (9%)	1576–1675 (81%) or 1692–1711 (14%)
59–89	103.6	1605–1613 (8%) or 1627–1668 (60%)	1576–1586 (2%) or 1596–1677 (92%) or 1696–1702 (1%)
64–94	118.4	1621–1659	1601–1676
69–99	116.8	1623–1659	1607–1672
74–104	114.1	1637–1664	1563–1569 (1%) or 1611–1672 (94%)
79–109	117.0	1555–1567 (18%) or 1637–1667 (50%)	1544–1573 (25%) or 1617–1675 (70%)
84–114	115.5	1551–1568 (31%) or 1649–1668 (37%)	1538–1573 (37%) or 1616–1677 (58%)
89–119	117.5	1548–1568 (35%) or 1650–1670 (33%)	1529–1574 (46%) or 1609–1635 (11%) or 1646–1675 (38%)
94–124	124.8	1553–1564 (36%) or 1658–1670 (32%)	1546–1574 (50%) or 1649–1677 (45%)
99–129	92.7	1664–1674	1555–1557 (1%) or 1657–1679 (94%)
104–134	78.3	1662–1674	1552–1563 (6%) or 1656–1679 (89%)
109–139	97.7	1664–1673	1656–1678
114–144	104.1	1665–1673	1659–1675
119–149	98.8	1664–1671	1659–1675

Figure 1: Offsets between radiocarbon ages on single tree-ring from this study and measurements on single tree-rings of the same calendar date reported by Stuiver (1993, corrected as described by Stuiver and Becker 1993). Colour figure

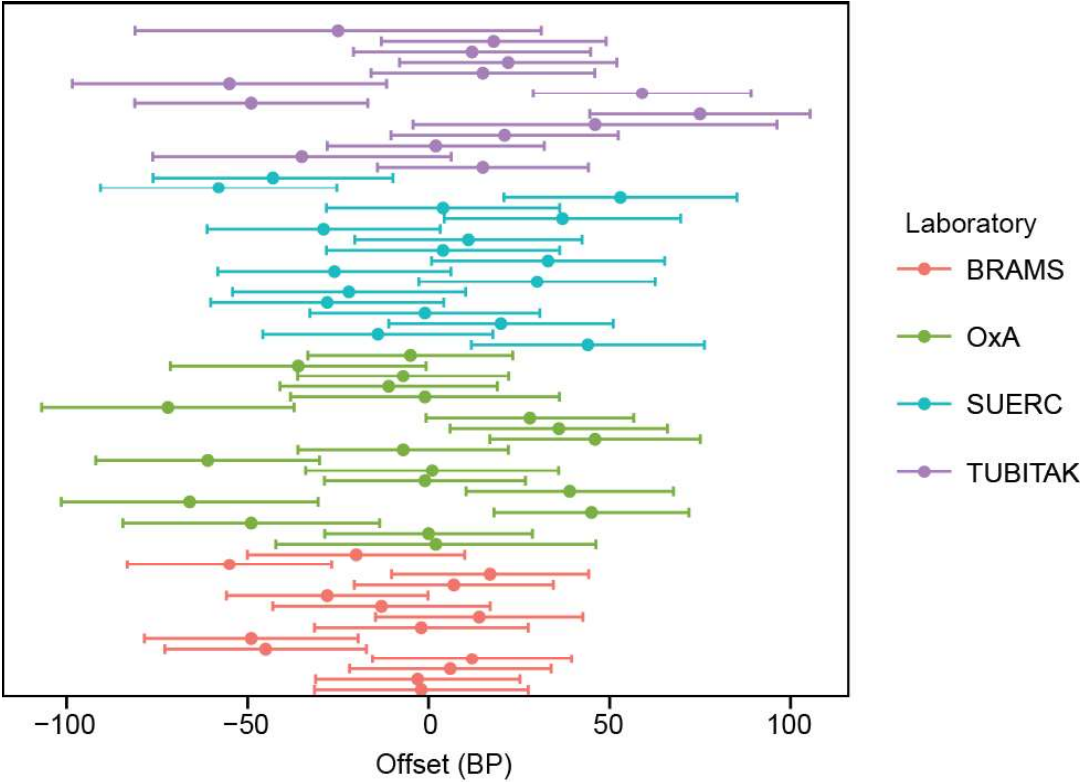


Figure 2: Probability distributions of dates from LED-A22. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the result of simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence. Distributions other than those relating to particular samples, correspond to aspects of the model. For example, the distribution 'SUERC-68040' is the estimated date of the final ring of this core. The large square brackets down the left-hand side of the diagram along with the CQL2 keywords (Bronk Ramsey 2009) define the model exactly.

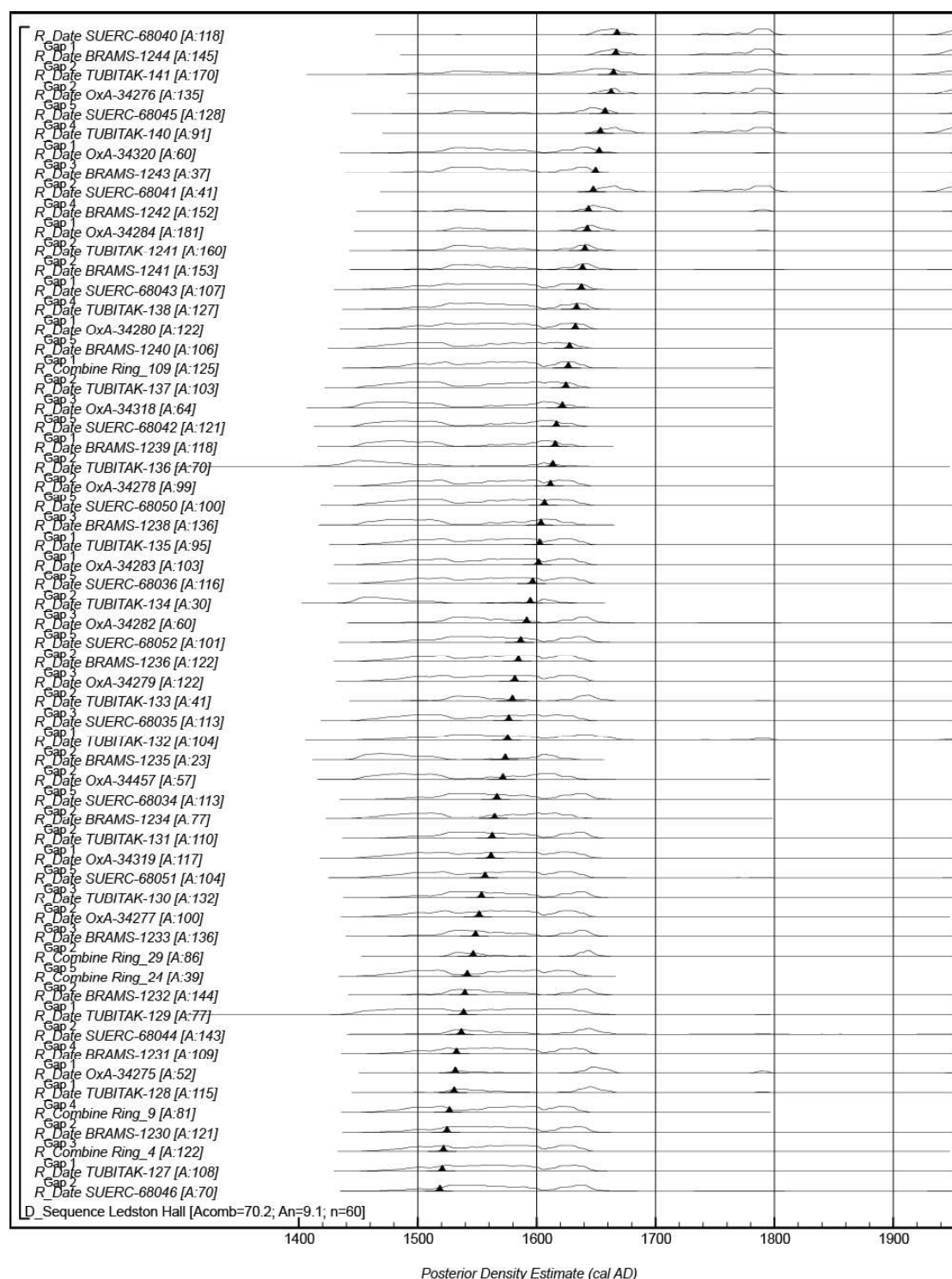


Figure 3: Probability distributions of dates from LED-A22 (a) BRAMS-, and (b) OxA-. The format is identical to that of Figure 2. The large square brackets down the left-hand side of the diagram along with the CQL2 keywords define the model exactly

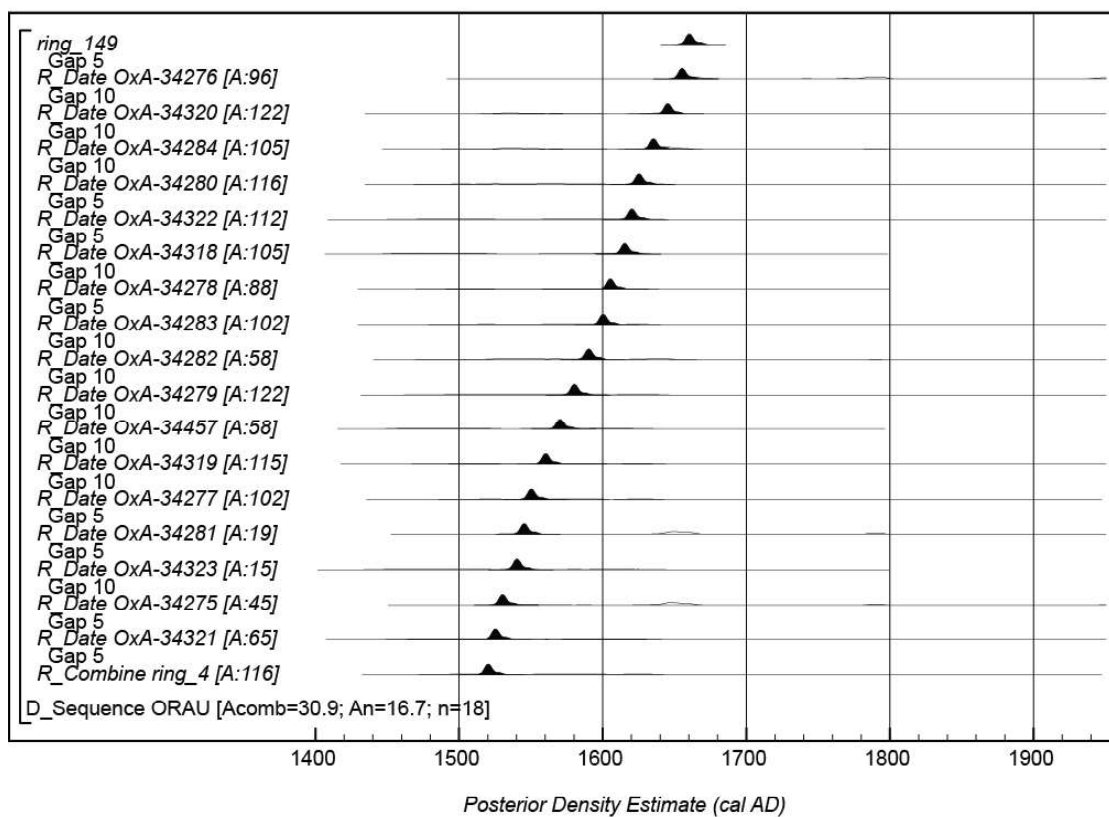
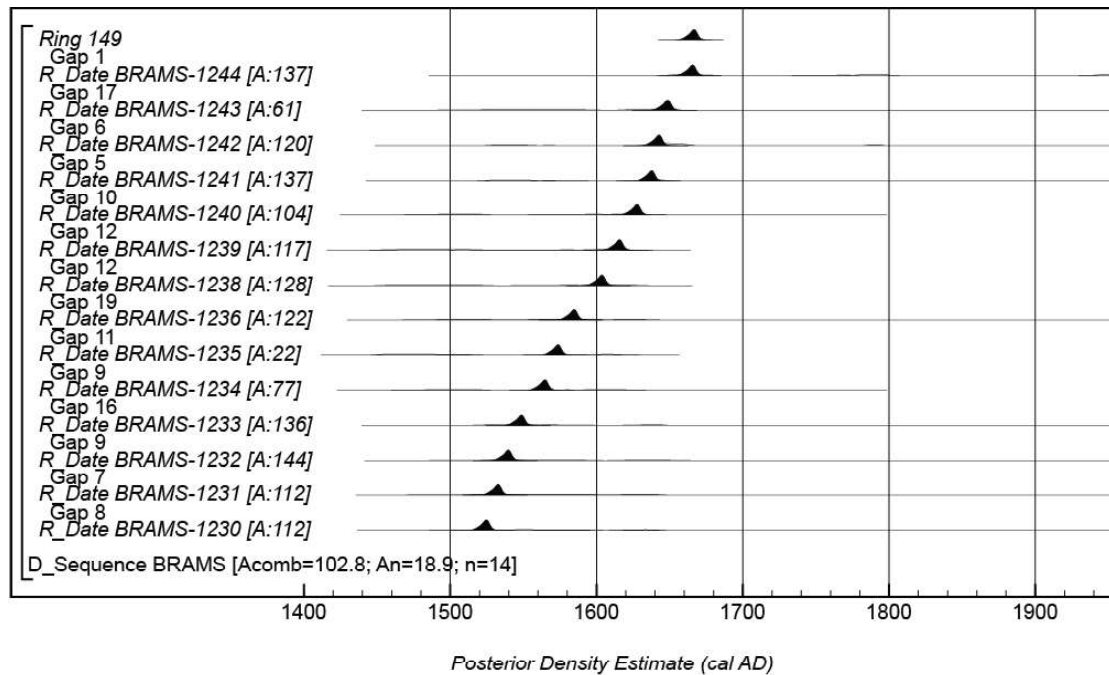


Figure 4: Probability distributions of dates from LED-A22 (a) SUERC, and (b) TUBITAK. The format is identical to that of Figure 2. The large square brackets down the left-hand side of the diagram along with the CQL2 keywords define the model exactly

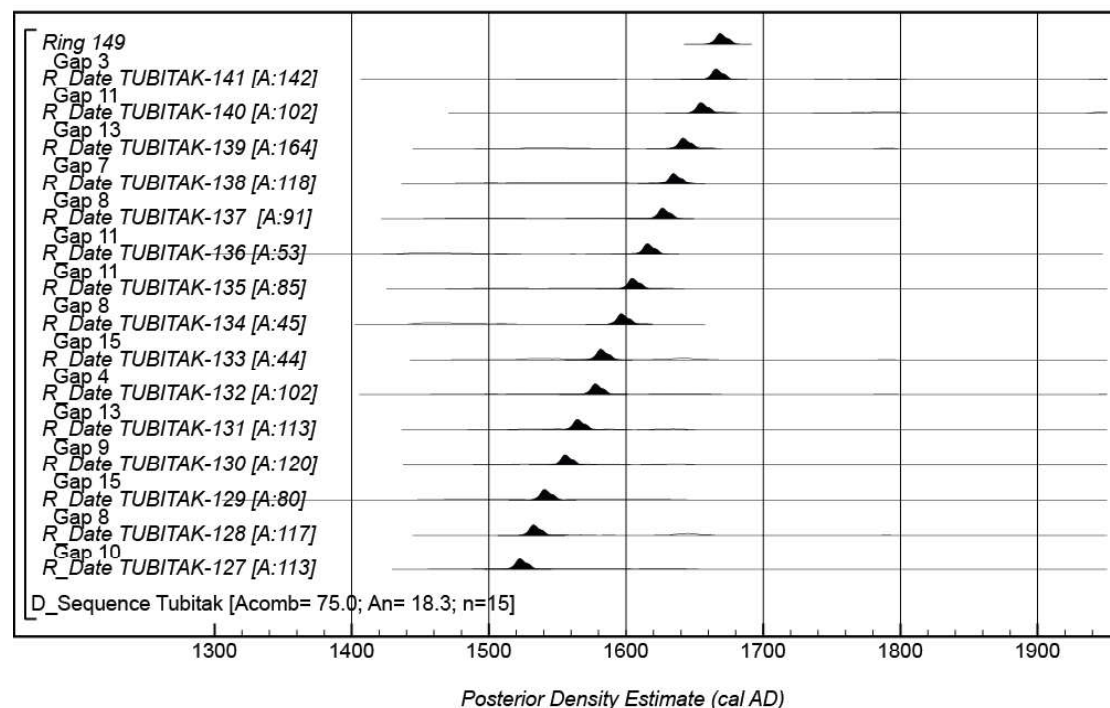
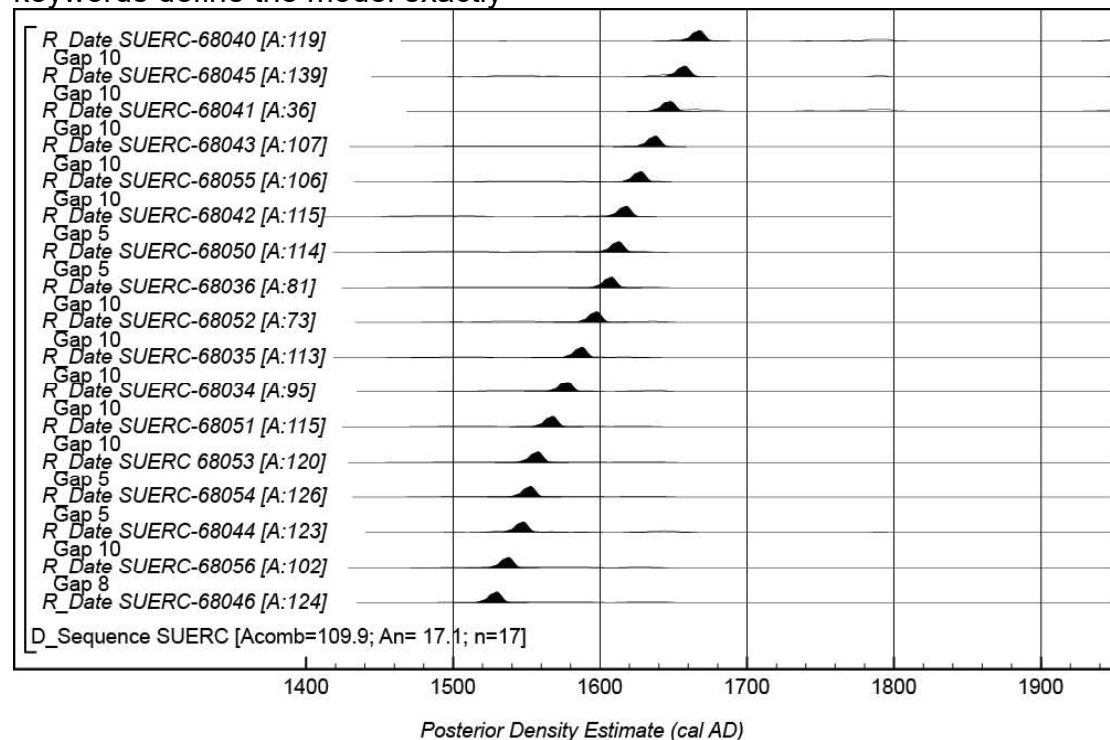


Figure 5: Posterior density estimates for the final ring of LED-A22, derived from the short wiggle-matches based on sequences of 29–30 tree-rings.
Colour figure

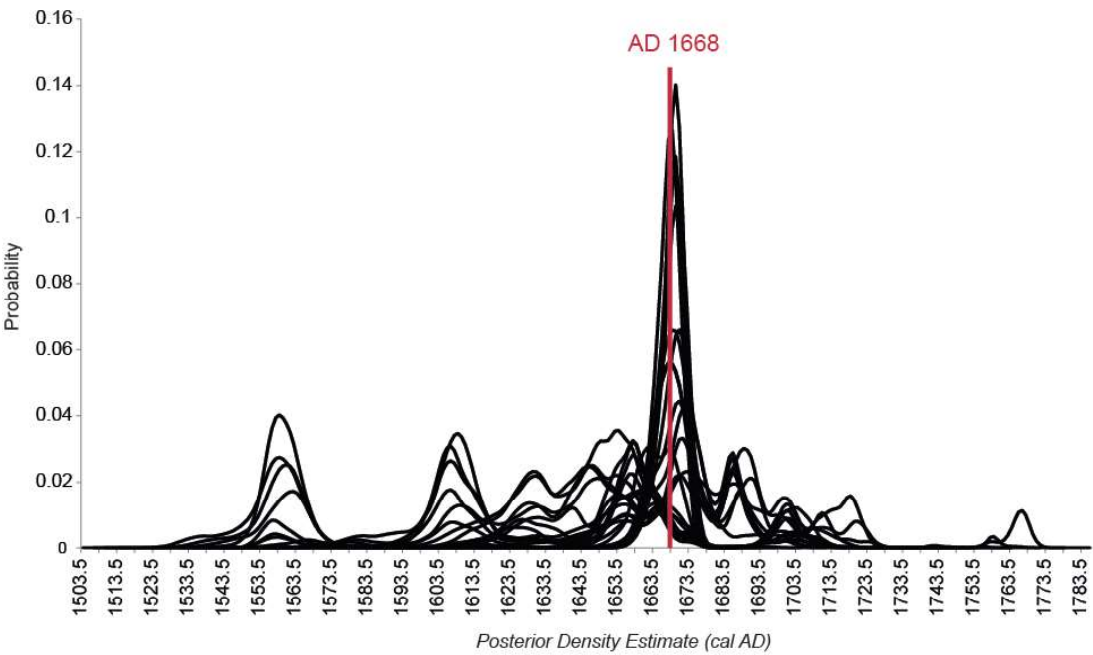


Figure 6: Radiocarbon ages of known-age tree-ring rings AD 1150–1668: single years (OxA-, SUERC-, GrA-, BRAMS-, TUBITAK-; this study, Bayliss *et al.* 2017, Tyers *et al.* 2009), decadal samples (Wk; Hogg *et al.* 2002), single-year and decadal samples (QL; Stuiver 1993 as corrected by Stuiver and Becker 1993; Stuiver *et al.* 1998), decadal and bi-decadal samples (UB; Hogg *et al.* 2002; Pearson *et al.* 1986), decadal and 23-year and 24-year samples (GrN: van der Plicht *et al.* 1995). Colour figure

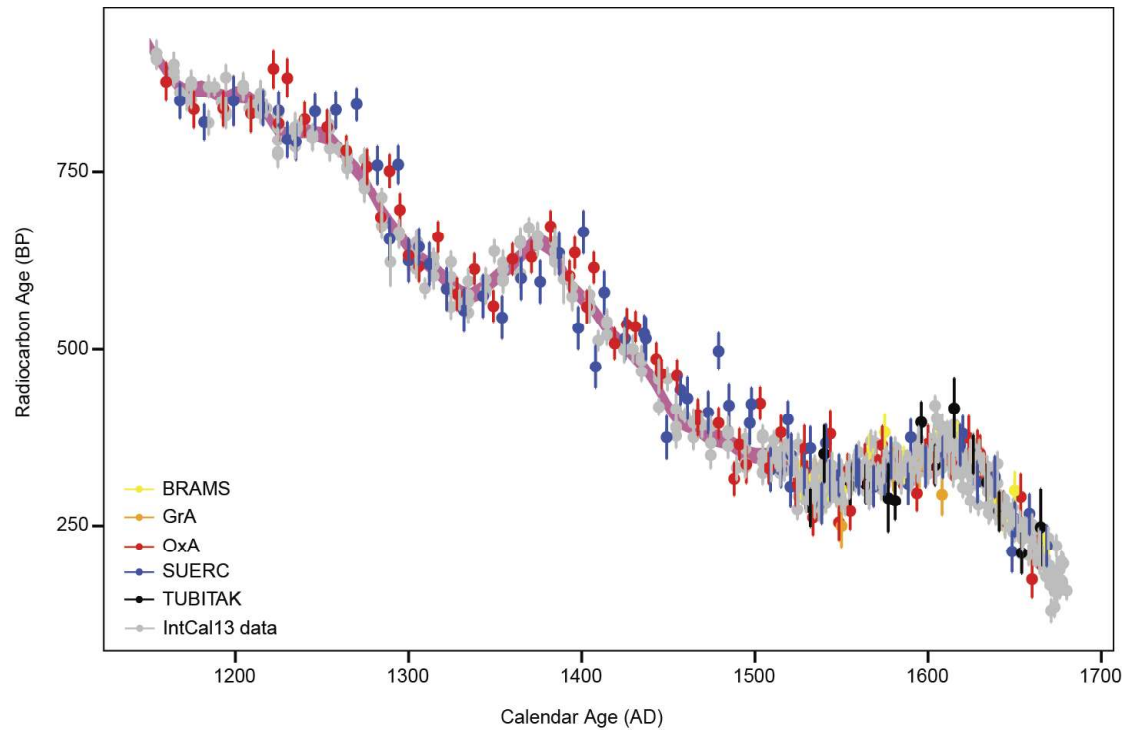


Figure 7: Radiocarbon ages of known-age tree-ring rings AD 1510–1670: single years (OxA-, SUERC-, GrA-, BRAMS-, TUBITAK-; this study, Bayliss *et al.* 2017, Tyers *et al.* 2009), decadal samples (Wk; Hogg *et al.* 2002), single-year samples (QL; Stuiver 1993 as corrected by Stuiver and Becker 1993; Stuiver *et al.* 1998), decadal and bi-decadal samples (UB; Hogg *et al.* 2002; Pearson *et al.* 1986), decadal and 23-year and 24-year samples (GrN: van der Plicht *et al.* 1995). Colour figure

